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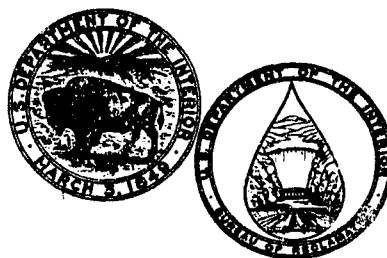
UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

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STUDIES OF ORIFICES FOR AUTOMATIC SPILLWAY GATE CONTROLS

Report No. HYD-596

HYDRAULICS BRANCH
DIVISION OF RESEARCH



OFFICE OF CHIEF ENGINEER
DENVER, COLORADO

SEPTEMBER 1969

Where approximate or nominal English units are used to express a value or range of values, the converted metric units in parentheses are also approximate or nominal. Where precise English units are used, the converted metric units are expressed as equally significant values. A table of conversion factors—BRITISH TO METRIC UNITS OF MEASUREMENT—is provided at the end of this report.

Report No. HYD-596

**STUDIES OF ORIFICES FOR AUTOMATIC
SPILLWAY GATE CONTROLS**

by
D. L. King

September 1969

**HYDRAULICS BRANCH
DIVISION OF RESEARCH**

UNITED STATES DEPARTMENT OF THE INTERIOR * BUREAU OF RECLAMATION
Office of Chief Engineer . Denver, Colorado

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ABSTRACT

Design of orifice filling systems for automatic spillway gate controls requires 3-place discharge coefficients. Limited tests were made on orifices having various unusual approach and exit configurations. Where appropriate, reference is made to results of previous research, indicating that further tests were unnecessary. Effects of unusual geometry are generally negligible. Guidelines are presented for correction of coefficients when such effects should be considered.

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DESCRIPTORS—/ *orifices/ *spillway gates/ *automatic control/ hydraulic models/ design/
hydraulics/ *discharge coefficients/ spillways/ research and development/ design criteria/
hydraulic structures/ spillway gates/ orifice flow/ hydraulic design

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PURPOSE

The purpose of this study was to determine discharge coefficients for orifices in unusual geometric configurations, to aid in the design of orifice filling systems for automatic spillway gate controls.

CONCLUSIONS

Based on present tests:

1. Upstream approach configurations were found to have negligible effect on discharge coefficients. The coefficients were within 1 percent of those determined for ideal approach conditions.
2. Coefficients for orifices in the wall of a pipe are affected by the wall curvature. The jet contraction is modified and the effective orifice area is increased over that for a corresponding plane orifice. The data did not reveal how these effects should be separated.
3. Opposing 1.9-inch orifices in a 10-inch pipe had no effect on the discharge coefficient.

Based on theory and tests performed by others:

1. The coefficient for orifice flow against a flat plate is unaffected unless the plate is within approximately one-half orifice diameter from the plane of the orifice. This conclusion is based on theory.
2. According to previous work by another experimenter, upward adjustment of discharge coefficients of about 3 percent could be expected with eccentric placement of the orifice in a pipe. The results were obtained with one edge of the orifice coincident with the pipe wall and with d/D ratios less than approximately 0.5.
3. The results of the present tests on unusual approach conditions and previous tests with eccentric orifice placement indicate that a cylindrical obstruction in the approach pipe would have a negligible effect on the orifice discharge coefficient.
4. Orifices spaced 2 feet apart in a vertical line should not affect the discharge coefficient. Potential theory suggests that pressure distribution at the inlet to each orifice would be unaffected by another orifice 2 feet away.

APPLICATIONS

The results of these tests are for the use of Bureau of Reclamation designers in designing structures requiring specific types of orifice controls. The criteria presented are generally applicable to any problem requiring knowledge of orifice discharge coefficients. However, the coefficients for the "less-than-ideal" configurations apply only to those particular configurations.

INTRODUCTION

Orifice controls have been used in connection with automatic spillway gates at several locations in the past few years. Use of such controls on future installations will depend upon the reliability of the computed flow rate through the orifices. The orifice discharge governs the relationship between spillway gate opening and reservoir elevation.

Accurate design requires 3-place discharge coefficients for 1- and 3-inch-diameter, square-edged, circular orifices in 10-gage plate, under heads up to 100 feet. Information on the following configurations was requested:

1. Orifice in a vertical plane
2. Orifice in a horizontal plane
3. Orifice in a vertical plane approached by two inverted 90° 6-inch elbows.

A determination of the effects, if any, of the following conditions on the discharge coefficients was also required:

1. Orifice discharging against a flat plate at various distances from the plane of the orifice
2. Three-inch orifice located eccentrically in the end of a 10-inch pipe, with a 4-inch-diameter cylindrical obstruction along the opposite wall of the pipe
3. One- and 2-inch-diameter orifices drilled normal to the wall of a 4-inch pipe, with flow into the pipe under heads of 3 to 15 feet
4. Two or three 2-inch orifices spaced 2 feet apart in a vertical line discharging into a 4-inch pipe
5. Two opposing orifices in the wall of a 4-inch pipe (unspecified orifice size)

Conclusions were reached by performing laboratory tests, through a library search with quotation of appropriate findings, and by reference to theory. In order to expedite the laboratory work, some tests were modified slightly from the requirements listed above.

TEST APPARATUS

The equipment used for investigating the effects of the three basic configurations listed above consisted of a 3-foot-diameter, 6-foot-long steel tank to which the orifices and approach piping were attached. Heads were measured at taps located at quarter-points on the periphery of the flange to which the orifice plates were attached. The taps were connected to open-tube water or mercury manometers, depending on the head. Discharges were measured with venturi meters which are a permanent part of the laboratory system.

The special conditions, also listed above, were investigated with a full scale model of the orifice control configuration for the spillway gates at Norton Dam. The system was enclosed in a 12-foot-high rectangular tank with a plexiglass viewing window on one side. Heads were measured with open-tube water manometers or with electronic pressure transducers. Discharges were measured with a v-notch weir located in a rectangular flume through which the discharge of the model passed. The weir was calibrated with the permanent venturi meters and checked by weighing the discharge.

INVESTIGATION

Orifice in a Vertical Plane

The test rig is shown in Figure 1A. Data points for a 3-inch orifice in a 10-gage plate, placed concentrically in the end of a 10-inch-diameter, 4-foot-long pipe are shown in Figure 2.

The coefficients have an average value of 0.607 for heads between 20 and 100 feet. Below 20 feet, the coefficients show quite a large scatter and general increase with decreasing head. These trends are caused by the jet clinging to the inner surface of the orifice, instead of springing clear at the upstream edge. The contraction of the jet is reduced, thus resulting in a corresponding increase in the discharge coefficient. The scatter results from the instability of this phenomenon.

¹King, H. W., Wisler, C. O., and Woodburn, J. G., "Hydraulics," Fifth Edition, John Wiley and Sons, Inc., New York, 1948, fig. 62, p 130.

Comparison of the coefficient curve with that obtained by Blackburn¹, shows slightly higher coefficients for the present data. However, the maximum difference is only about 1 percent. This difference could easily be due to experimental errors in either the present or previous tests, or both.

Reliable data could not be obtained for the 1-inch orifice because of difficulties in accurately measuring the very low discharges. The coefficients should be the same as those indicated by Blackburn's curves.

Orifice in a Horizontal Plane

Because the tests on the orifice in the vertical plane resulted in coefficients nearly equal to previously accepted values, studies of an orifice in a horizontal plane were not made. Only for low heads, when the head and velocity exhibit an appreciable variation from top to bottom of the pipe, would the coefficients for the vertical plane be expected to differ from those for the horizontal plane.

Orifice in a Vertical Plane Approached by Two Inverted 90°, 6-inch Elbows

The test rig is shown in Figure 1B. Figure 2 shows that the coefficients for low heads follow a trend similar to that with a straight approach. For heads above approximately 20 feet the coefficients are less than 1 percent lower than the values from Blackburn's curves. Tests on a 1-inch orifice were therefore considered unnecessary.

Orifices in Wall of Pipe

The full-scale model of the Norton system, Figure 3, was used to study some of the remaining conditions. Several different size orifices in the side of a 10-inch-inside-diameter pipe with 1/4-inch wall thickness were studied, instead of 1- and 2-inch orifices in a 4-inch pipe as stated in the Introduction. Figure 4 summarizes experimental coefficients for orifice diameters of 4, 1.90, 1.72, 1.25, and 1.05 inches.

There appears to be no correlation between the discharge coefficient and orifice size. The author feels that the effect of wall thickness may have obscured the effect of orifice size. The orifices were cut so that the sides of the orifice were parallel. Therefore, the orifice size would affect the shape of the spring point of the

flow. It is possible that the general form of the contracted jet was different for the various test orifices. Additional studies would be necessary to isolate the effect of pipe thickness.

To determine the relationship, if any, between the discharge coefficient and the angle of side contraction (β), the data were plotted with the data of von Mises² Figure 5. b/B (or d/D) was taken as 0.0 because the flow through the orifice originates in a large body of water. Figure 5 fails to show any relationship between the contraction angle and the discharge coefficient, unless the points for the 1.25- and 1.72-inch orifices are disregarded.

Figure 6 gives the percentage correction that must be added to plane orifice area to obtain true area for various ratios of pipe diameter to orifice diameter. The correction is essentially negligible for all but the 4-inch orifice ($D/d = 2.62$, correction = 2 percent). Corrected coefficients are summarized in Table 1.

Opposing Orifices

Two 1.90-inch orifices were placed directly opposite each other in the wall of the 10-inch-inside-diameter pipe. Figure 7 shows that impingement of one jet on the other in this installation does not affect the orifice discharge coefficient. This condition is analogous to that of a single jet discharging against a flat plate (described below). Larger orifices might influence one another because of the increased distance between the plane of the orifice and the vena contracta. Assuming this length to be one-half orifice diameter, the required orifice diameter would be equal to the diameter of the pipe in which it is placed. This is, of course, an unrealistic condition.

Orifice Discharging Against A Flat Plate

An obstruction to a jet will have no effect if the obstruction is located downstream from the vena contracta. A generally accepted rule is that the vena contracta is located approximately one-half orifice diameter downstream from the plane of the orifice. It is doubtful that such restrictive conditions would ever be required in an orifice control system. No tests were performed.

Orifice Located Eccentrically in Pipe with Obstruction

No tests were made on this configuration. Beitler and Masson, in a 1949 paper³, describe findings that for d/D ratios less than about 0.5, coefficients for orifices with one edge coincident to the side of the pipe were about 3 percent higher than for concentric orifices with equal d/D ratios. The effect of the cylindrical obstruction is unknown, but this effect would not be expected to be large, especially in view of the tests on unusual approach conditions described above.

Orifices in a Vertical Line

Orifices placed 2 feet apart in a vertical line would not be expected to influence the discharge coefficient. Potential theory suggests that the pressure distribution of one orifice would not be influenced by flow through the other. This condition was not investigated during these studies.

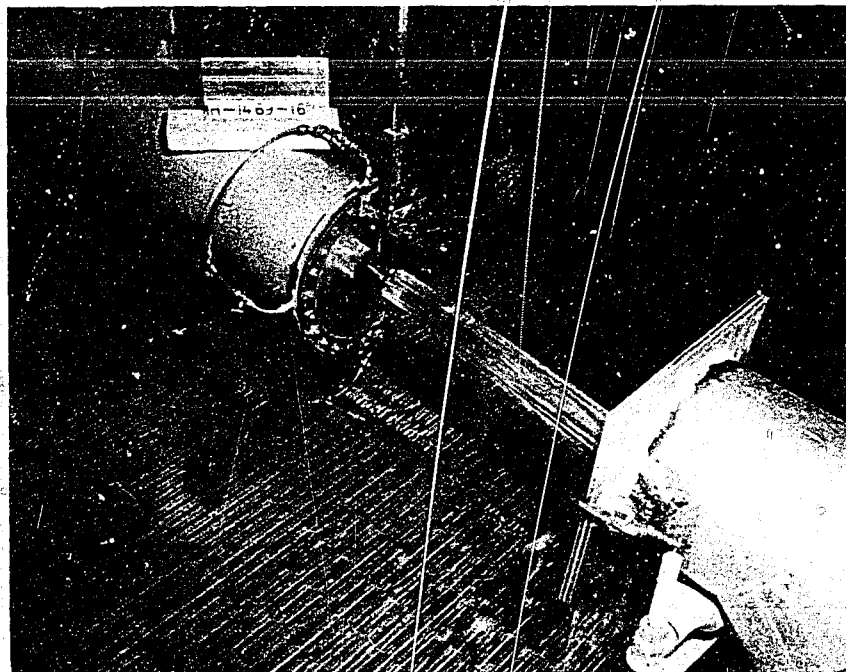
Table 1

DISCHARGE COEFFICIENTS WITH AND WITHOUT CORRECTION FOR CHANGE IN EFFECTIVE AREA

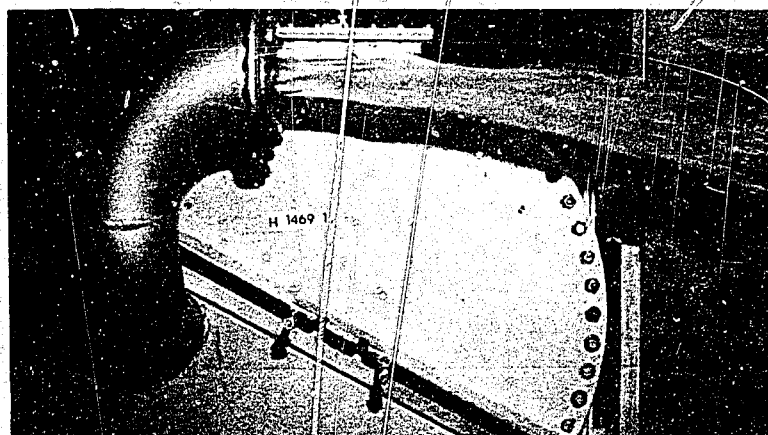
Orifice size, inches	Cd based on plane area	Cd based on true area
4	0.601	0.589
1.9	.625	.622
1.72	.539	.539
1.25	.582	.582
1.05	.626	.626

² Elementary Mechanics of Fluids, Hunter Rouse, John Wiley and Sons, Inc., New York, 1946, Table I, p 57.

³ Beitler, S. K. and Masson, D. J., "Calibration of Eccentric and Segmental Orifices in 4- and 6-inch Pipe Lines," Transactions of ASME, 1949, 71(7), pp 751-755.



A. Test rig for 3-inch orifice placed concentrically in 10-inch-diameter, 4-foot-long pipe. Photo PX-D-64863

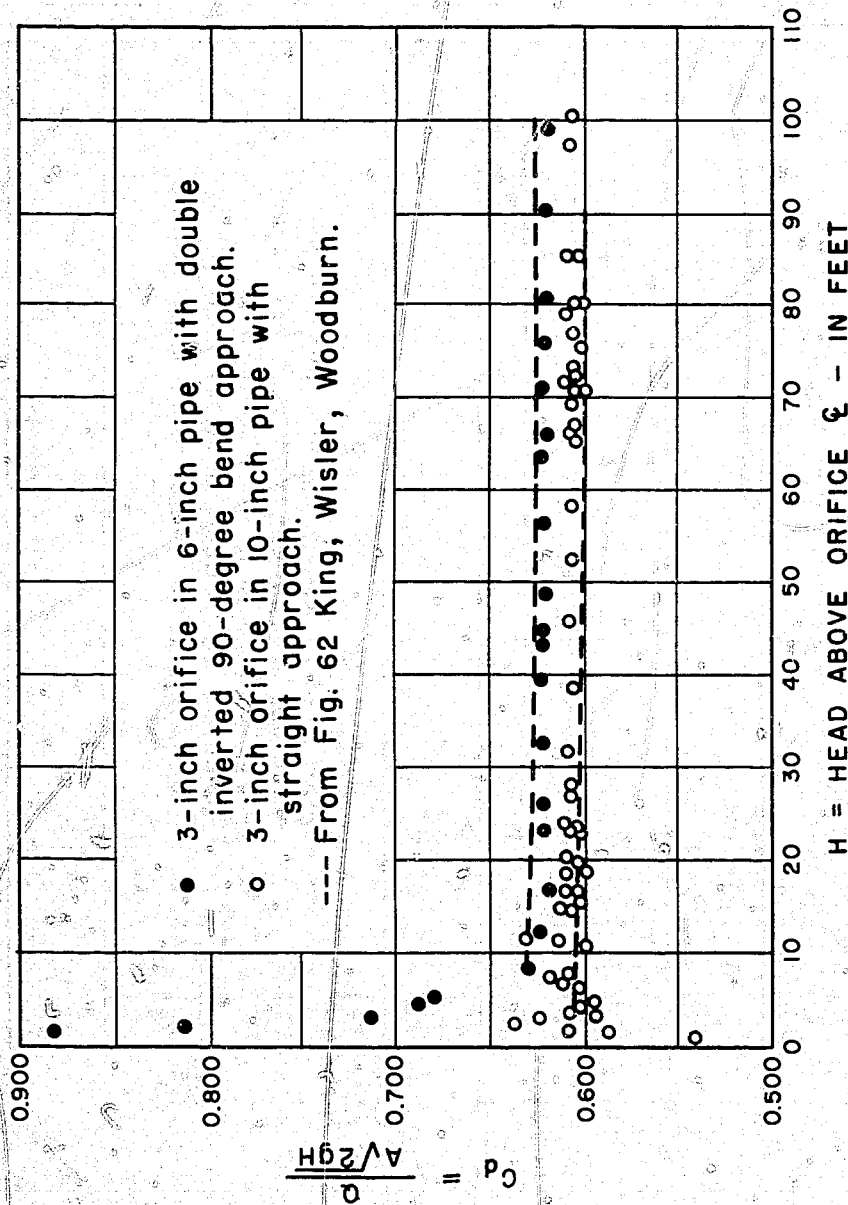


B. Test rig for 3-inch orifice in 6-inch-diameter pipe, approached by two inverted 90° elbows. Photo PX-D-64862

ORIFICES FOR AUTOMATIC SPILLWAY GATE CONTROLS

Test Rigs for Determination of Effect of Upstream Approach Configuration

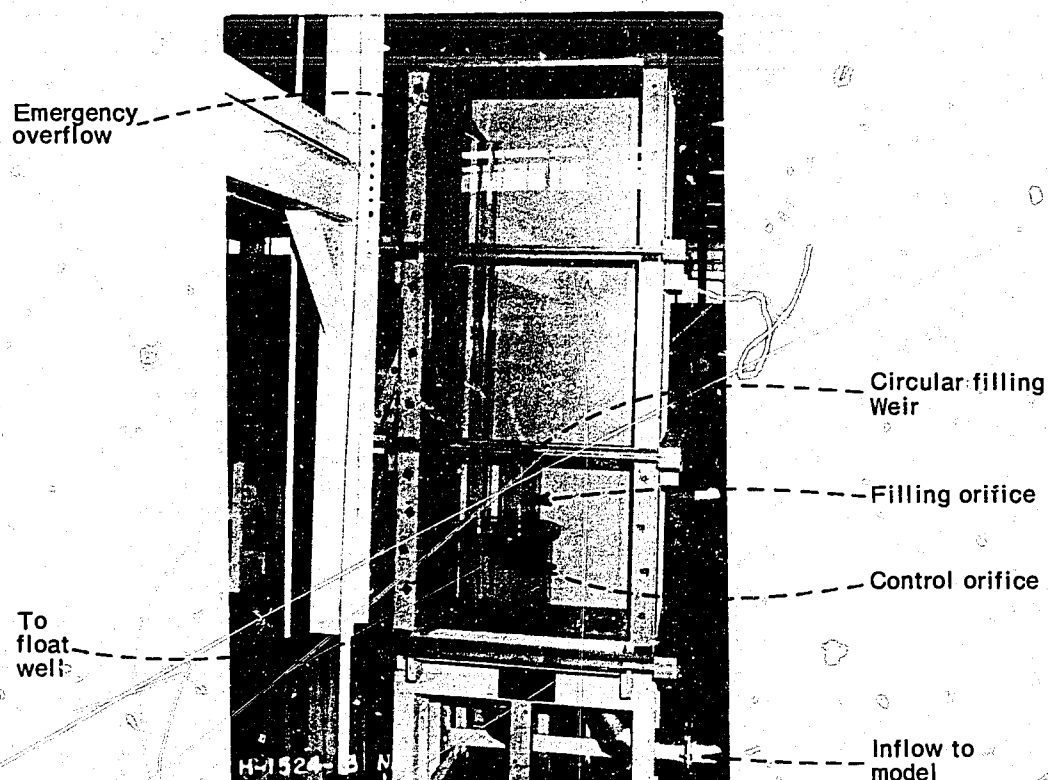
FIGURE 2
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ORIFICES FOR AUTOMATIC SPILLWAY GATE CONTROLS

Effect of Upstream Approach

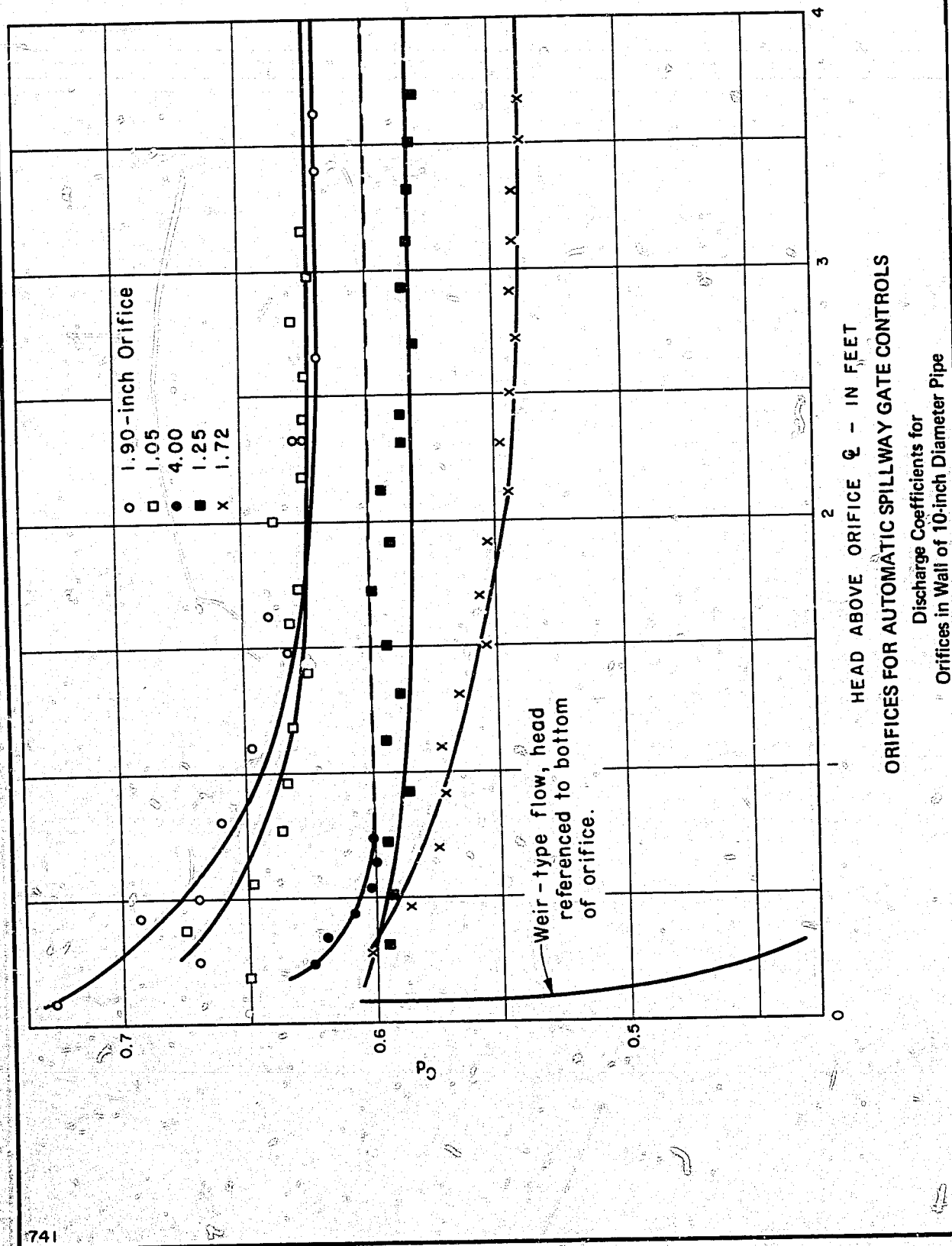
FIGURE 3
REPORT HYD-596

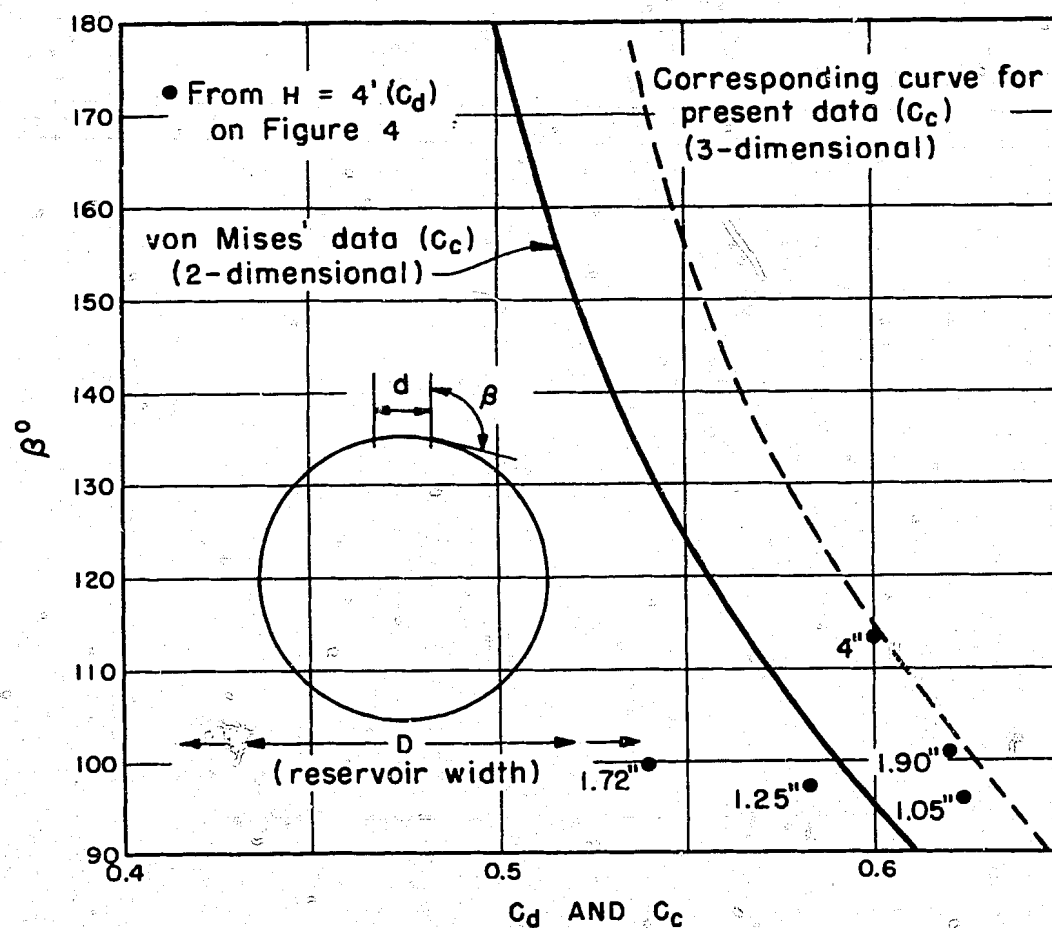


ORIFICES FOR AUTOMATIC SPILLWAY GATE CONTROLS

Full Scale Model of Filling
System for Norton Dam Spillway Gate Control

FIGURE 4
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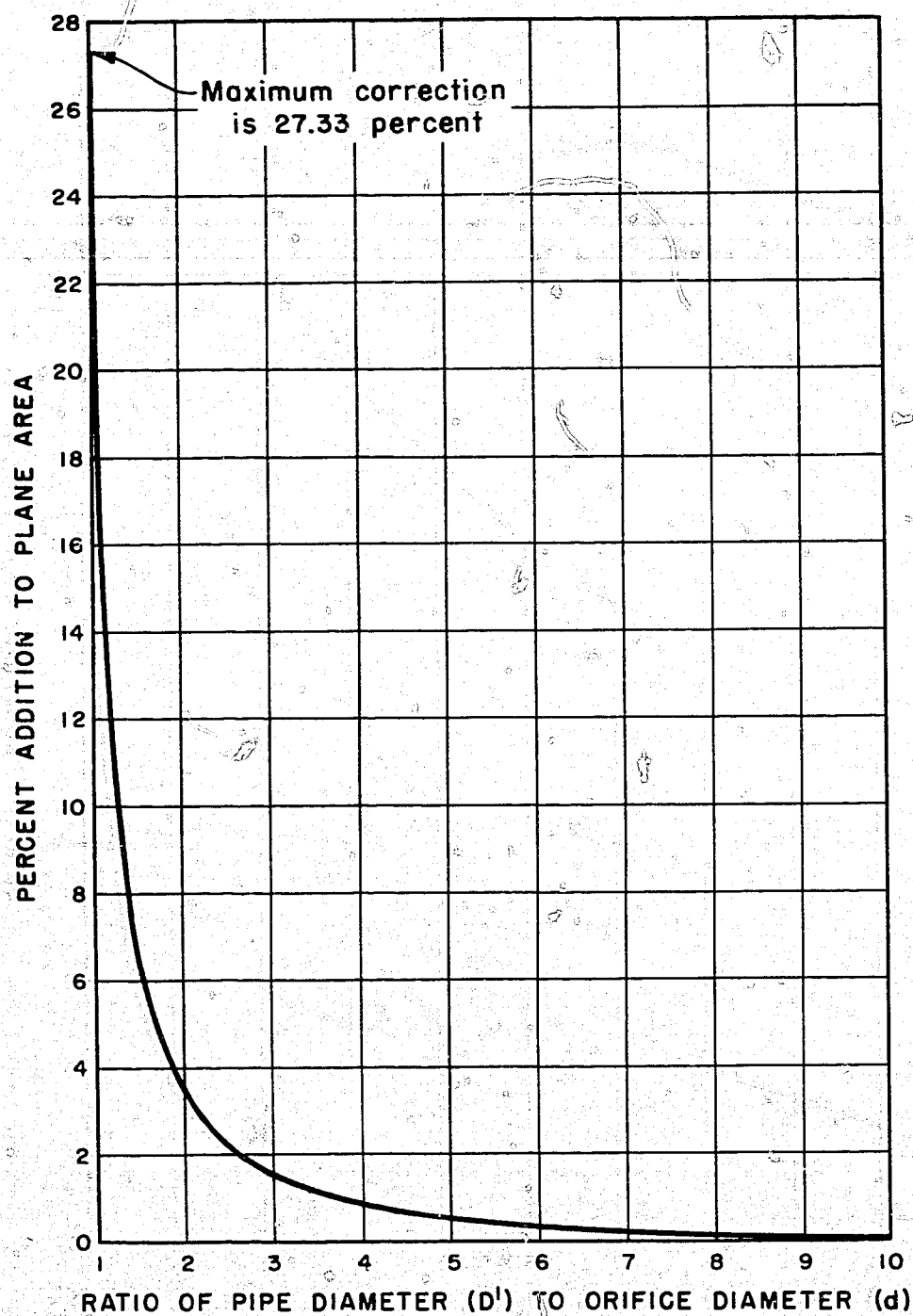




ORIFICES FOR AUTOMATIC SPILLWAY GATE CONTROLS

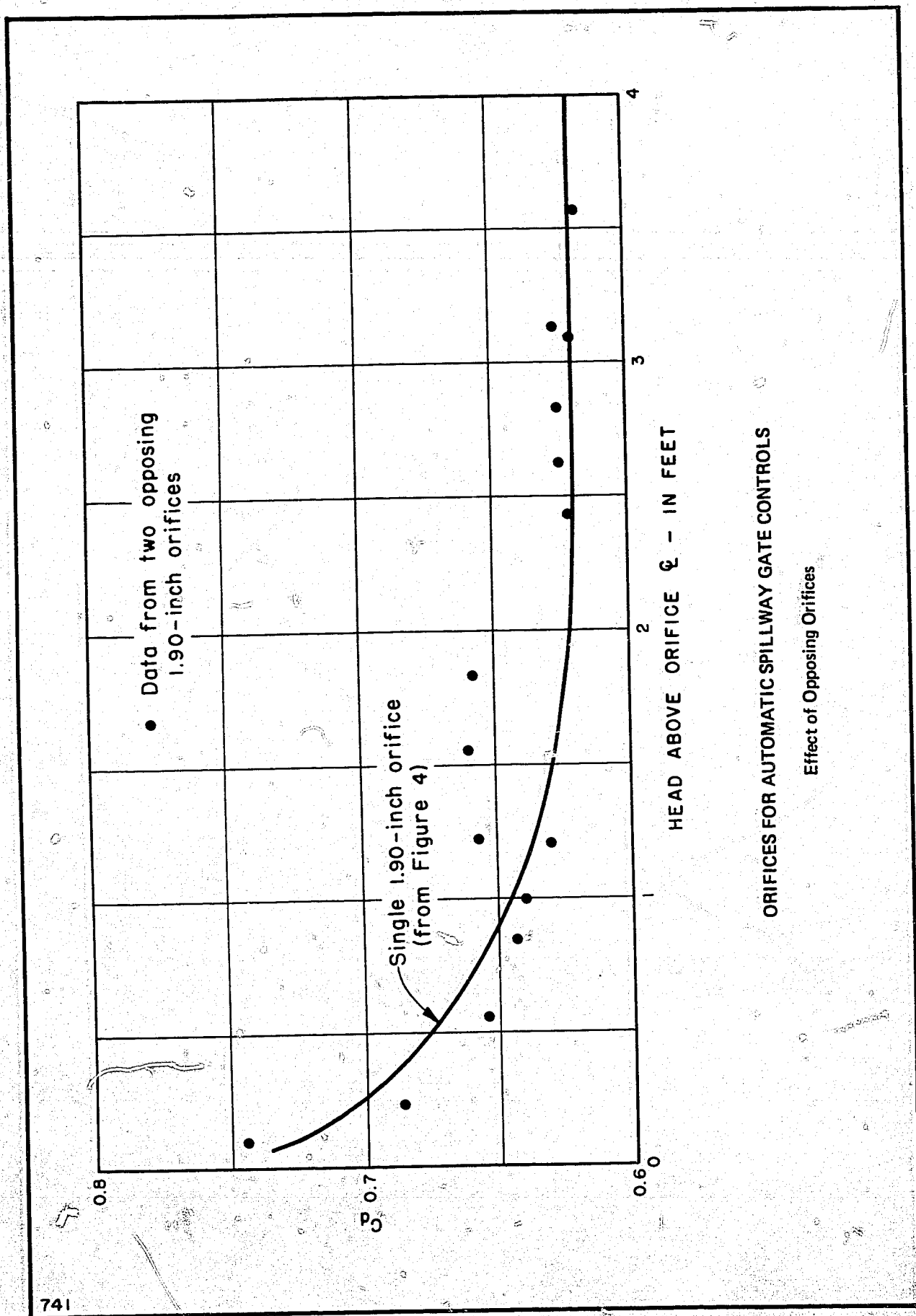
Correlation of Discharge Coefficient with Angle of
Side Contraction, Orifices in Wall of 10-inch Diameter Pipe

FIGURE 6
REPORT HYD-596



ORIFICES FOR AUTOMATIC SPILLWAY GATE CONTROLS

Area Correction for Orifices in Wall of Pipe



ORIFICES FOR AUTOMATIC SPILLWAY GATE CONTROLS
Effect of Opposing Orifices

CONVERSION FACTORS--BRITISH TO METRIC UNITS OF MEASUREMENT

The following conversion factors adopted by the Bureau of Reclamation are those published by the American Society for Testing and Materials (ASTM Metric Practice Guide, January 1964) except that additional factors (*) commonly used in the Bureau have been added. Further discussion of definitions of quantities and units is given on pages 10-11 of the ASTM Metric Practice Guide.

The metric units and conversion factors adopted by the ASTM are based on the "International System of Units" (designated SI for Systeme International d'Unites), fixed by the International Committee for Weights and Measures; this system is also known as the Giorgi or MKSA (meter-kilogram (mass)-second-ampere) system. This system has been adopted by the International Organization for Standardization in ISO Recommendation R-31.

The metric technical unit of force is the kilogram-force; this is the force which, when applied to a body having a mass of 1 kg, gives it an acceleration of 9.80665 m/sec/sec, the standard acceleration of free fall toward the earth's center for sea level at 45 deg latitude. The metric unit of force in SI units is the newton (N), which is defined as that force which, when applied to a body having a mass of 1 kg, gives it an acceleration of 1 m/sec/sec. These units must be distinguished from the (inconstant) local weight of a body having a mass of 1 kg; that is, the weight of a body is that force with which a body is attracted to the earth and is equal to the mass of a body multiplied by the acceleration due to gravity. However, because it is general practice to use "pound" rather than the technically correct term "pound-force," the term "kilogram" (or derived mass unit) has been used in this guide instead of "kilogram-force" in expressing the conversion factors for forces. The newton unit of force will find increasing use, and is essential in SI units.

Table I

QUANTITIES AND UNITS OF SPACE

Multiply	By	To obtain
LENGTH		
Mil.	25.4 (exactly)	Micron
Inches	25.4 (exactly)	Millimeters
	2.54 (exactly)*	Centimeters
Feet	30.48 (exactly)	Centimeters
	0.3048 (exactly)*	Meters
	0.0003048 (exactly)*	Kilometers
Yards	0.9144 (exactly)	Meters
Miles (statute)	1,609.344 (exactly)*	Meters
	1.609344 (exactly)	Kilometers
AREA		
Square inches	6.4516 (exactly)	Square centimeters
Square feet	929.03*	Square centimeters
	0.092903	Square meters
Square yards	0.836127	Square meters
Acres	0.404689*	Hectares
	4,046.9*	Square meters
	0.00404689*	Square kilometers
Square miles	2.58999	Square kilometers
VOLUME		
Cubic inches	16.3871	Cubic centimeters
Cubic feet	0.0283168	Cubic meters
Cubic yards	0.764555	Cubic meters
CAPACITY		
Fluid ounces (U.S.)	29.5737	Cubic centimeters
	28.5729	Milliliters
Liquid pints (U.S.)	0.473179	Cubic decimeters
	0.473166	Liters
Quarts (U.S.)	946.358*	Cubic centimeters
	0.946331*	Liters
Gallons (U.S.)	3,785.43*	Cubic centimeters
	3.78543	Cubic decimeters
	3.78533	Liters
	0.00378543*	Cubic meters
Gallons (U.K.)	4.54609	Cubic decimeters
	4.54596	Liters
Cubic feet	28.3160	Liters
Cubic yards	764.55*	Liters
Acre-feet	1,233.5*	Cubic meters
	1,233,500*	Liters

Table II
QUANTITIES AND UNITS OF MECHANICS

Multiply	By	To obtain
MASS		
Grains (1/7,000 lb)	64.79891 (exactly)	Milligrams
Troy ounces (480 grains)	31.1035	Grams
Ounces (avdp)	28.3495	Grams
Pounds (avdp)	0.45359237 (exactly)	Kilograms
Short tons (2,000 lb)	907.185	Kilograms
Long tons (2,240 lb)	1,016.05	Metric tons
		Kilograms
FORCE/AREA		
Pounds per square inch	0.070307	Kilograms per square centimeter
	0.689476	Newtons per square centimeter
Pounds per square foot	4.88243	Kilograms per square meter
	47.8803	Newtons per square meter
MASS/VOLUME (DENSITY)		
Ounces per cubic inch	1.72999	Grams per cubic centimeter
Pounds per cubic foot	16.0185	Kilograms per cubic meter
	0.0160185	Grams per cubic centimeter
Tons (long) per cubic yard	1.32894	Grams per cubic centimeter
MASS/CAPACITY		
Ounces per gallon (U.S.)	7.4893	Grams per liter
Ounces per gallon (U.K.)	8.2362	Grams per liter
Pounds per gallon (U.S.)	119.828	Grams per liter
Pounds per gallon (U.K.)	99.779	Grams per liter
BENDING MOMENT OR TORQUE		
Inch-pounds	0.011521	Meter-kilograms
	1.12985×10^6	Centimeter-dynes
Foot-pounds	0.138255	Meter-kilograms
	1.35582×10^7	Centimeter-dynes
Foot-pounds per inch	5.4431	Centimeter-kilograms per centimeter
Ounce-inches	72.008	Gram-centimeters
VELOCITY		
Feet per second	30.48 (exactly)	Centimeters per second
	0.3048 (exactly)	Meters per second
Feet per year	0.865873×10^{-6}	Centimeters per second
Miles per hour	1.609344 (exactly)	Kilometers per hour
	0.44704 (exactly)	Meters per second
ACCELERATION*		
Feet per second ²	0.3048*	Meters per second ²
FLOW		
Cubic feet per second (second-feet)	0.028317*	Cubic meters per second
Cubic feet per minute	0.4719	Liters per second
Gallons (U.S.) per minute	0.06309	Liters per second
FORCE*		
Pounds	0.453592*	Kilograms
	4.4482*	Newtons
	4.4482×10^{-5} *	Dynes

Multiply	By	To obtain
WORK AND ENERGY*		
British thermal units (Btu)	0.252*	Kilogram calories
	1,055.06	Joules
Btu per pound	2.326 (exactly)	Joules per gram
Foot-pounds	1.35582*	Joules
POWER		
Horsepower	745.700	Watts
Btu per hour	0.293071	Watts
Foot-pounds per second	1.35582	Watts
HEAT TRANSFER		
Btu in./hr ft ² deg F (k, thermal conductivity)	1.442	Milliwatts/cm deg C
	0.1240	Kg cal/hr m deg C
Btu ft/hr ft ² deg F (C, thermal conductance)	1.4880*	Kg cal/m/hr m ² deg C
	0.688	Milliwatts/cm ² deg C
	4.882	Kg cal/hr m ² deg C
Deg F hr ft ² /Btu (R, thermal resistance)	1.781	Deg C cm ² /milliwatt
Btu/lb deg F (c, heat capacity)	4.1868	J/g deg C
Btu/lb deg F	1.000*	Cal/gram deg C
ft ² /hr (thermal diffusivity)	0.2581	cm ² /sec
	0.08220*	M ² /hr
WATER VAPOR TRANSMISSION		
Grains/hr ft ² (water vapor transmission)	16.7	Grams/24 hr m ²
Perms (permeance)	0.659	Metric perms
Perm-inches (permeability)	1.87	Metric perm-centimeters

Table III
OTHER QUANTITIES AND UNITS

Multiply	By	To obtain
Cubic feet per square foot per day (seepage)	304.8*	Liters per square meter per day
Pound-seconds per square foot (viscosity)	4.8824*	Kilogram second per square meter
Square feet per second (viscosity)	0.092903*	Square meters per second
Fahrenheit degrees (change)*	5/9 exactly	Celsius or Kelvin degrees (change)*
Volts per mil	0.03937	Kilovolts per millimeter
Lumens per square foot (foot-candles)	10.764	Lumens per square meter
Ohm-circular mils per foot	0.001882	Ohm-square millimeters per meter
Milliampes per cubic foot	35.3147*	Milliampes per cubic meter
Milliamps per square foot	10.7639*	Milliamps per square meter
Gallons per square yard	4.527219*	Liters per square meter
Pounds per inch	0.17858*	Kilograms per centimeter

ABSTRACT

Design of orifice filling systems for automatic spillway gate controls requires 3-place discharge coefficients. Limited tests were made on orifices having various unusual approach and exit configurations. Where appropriate, reference is made to results of previous research, indicating that further tests were unnecessary. Effects of unusual geometry are generally negligible. Guidelines are presented for correction of coefficients when such effects should be considered.

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